ACOUSTICAL QUALITY IN VIOLIN FAMILY INSTRUMENTS
The topics of the present article concerns the studies in the field of musical acoustics applied to stringed instruments. Italy represents no doubt one of the most important cultural reference point in such a field. In fact, during the centuries, Italy has registered an enormous increase in the craftmaking of these instruments with respect to all other countries. The fame that has marked the art of the Italian lutemakers in the past is still very evident, especially in Cremona, to the extent that it has dimmed the study of the Italian tradition and culture of stringed-instrument making that support the professional practical activity. In this kind of culture, the study of stringed instruments technology, as a part of the vast field of systematic musicology, is included. This is a reference point for musical acoustics, that in Italy has represented a portion of a scientific legacy dating from the end of the Nineteenth century. In fact, the approach to acoustics can be described as the slow flowing of a romantic formulation towards the acquisition of new techniques of research, above all as regards to the proceedings of non-destructive methods of restoration. Nowadays, the stringed instruments technology, which is actually connected with organology, has become a promoter for a more correct evaluation of the acoustic characteristics of stringed instruments, that is to say, of high quality sound sources.

As for the study of musical instruments in their old forms, we fortunately have both iconographic and bibliographic sources. As a matter of fact, the scientific methods concerning any hand-made article are always to be taken into account in order to seriously study the acoustic characteristics of every musical instrument. The rapporteurs can, therefore, take sides about functions and aims of acoustics, and also about the usage of musical instruments and their reconstructions according to new sound characteristics. This tradition must be specifically deep-rooted in culture, in the knowledge of productive progress, and in the possible historical relationships that are emphasized in a particular musical event. It can be said that studying the acoustics of a musical instrument means to play upon the events that preceeds its icon by transmuting its sensory results thanks to the demythisation of mechanical action.

Thus, the acoustic engineer's job turns out to the a simple ring of a chain of interpretations that are meant to be objective but that are, nevertheless, always partially subjective. This analysis, moreover, has to be contextually integrated with an investigation of the interactions between music and culture: in fact, important information about the way in which a certain instrument plays or is played helps to better define the taxonomic criteria that the analysis itself must bring on. Finally, research can be enriched by specific empirical studies about what is actually to be regarded as a musical instrument Guizzi [1], When we define an object as musical instrument, we actually elevate it, and we do that after identifying it and testing its possible phonic powers, as well as by expecting it to possess them. This is what musical acoustics does with a sound object before it is given its symbolic value. What acoustics actually does is to break that mechanism: it turns out to be what quantum mechanics would call an observer of an event that possibly implies the distortion of pre-existing properties. The same thing can be said about acoustics delays in our country, though it must be pointed out that Italian acoustics has anyway made good contributions, at least in the first Romantic Age, when stringed instruments were classified as 'rubbing instruments' in the Hornbostel-Sachs system.

In Italy musical acoustics represents the paradigm of a subject which is slow to make a name for itself, but that anyway shows all the characteristics of an ancient traditional discipline. In particular, stringed instruments acoustics clearly shares the methodological and teaching lacks of our country's musical background: it is in fact, an old discipline based upon a pure nineteenth-century culture, as in it there is no development of new ideas and of the same interdisciplinary scientific knowledge that we can find in organology. The history of stringed instruments acoustics begins with the lutemakers' tradition: in short, it begins in one of the greatest and liveliest period of our history. The slow acquisition of scientifics methods lead to a clear-cut separation between traditional craftsmanship and acoustic analysis of vibratory systems. Anyway,
inside Italian culture this parting between craftsman and scientist kept on diminishing as time passed by: in fact, it maintained a close relationship with the stringed-instrument making high tradition as opposed to scientific research, by giving rise to figures like music lovers, charlatans, scientists-lutemakers, and acoustics amateurs. In the Nineteenth century, Italy was in line with German culture or with French physicist Savart's studies. Among these connoisseurs, mention must be made of physicist Pietro Blaserna [2], who in 1875, following German scientist Hermann von Helmholtz, gave currency to acoustics with special regards for the auditory physiological theory. A difference in quality, still based on classic lute-making ideas, could be perceived from 1930 to 1950, when acoustics seemed to carve out a place for itself inside our research institutes. In the years preceeding Second World War, several personalities worked in Rome at the National Institute of Acoustics O. M. Corbino, where they were given good technological means. The scientists at the Institute of Acoustics in Rome analysed stringed instruments following electroacoustic methods (1938-39, 1940, 1941), so that they could estimate the ‘sound excellence’ by ‘objective’ methods that they had got out of previous well-known international works. In particular, Pasqualini [3] exemplified electrostatic excitement method as follows: first he laid a thin-foil on the wooden surface of the instrument, and then he made it vibrate by a short-distance positioned electrode generating an electrostatic field. He also used other ‘mixed’ methods so that he could better put them in evidence with the microphonic systems which were adopted at that time.

Violin is no doubt the instrument that, during the centuries, has mostly fascinated lutemakers as well as active and passive users, which has also given rise to embellishments of no technical interest and to fanciful, sometimes even aberrant, conclusions Tiella [4]. These conclusions, that can still be found in our contemporary essays, supported a feverish search for the secrets of lutemakers of genius like Stradivari, and above all for the geometrical marking process of instruments shapes and for the presumed chemical methods that old lutemakers would use. He unwillingly created this historical reference following a precise aesthetic-acoustic point of view, while not recognizing the same phonic importance to violins that are still being made by modern lutemakers even if they are modelled upon original archetypes. Essentially, in those years Italian researchers did not modify their ways of working. On the one hand, in fact, some of them evaluated the acoustic phenomena by following their strong ideals of patriotic lutemakers, as we can see in Cremona School; on the other hand, an attempt was made to dissect the sound object far beyond its own musical and material characteristics. As for acoustic research in Italy during the post-war period, an intermediate position is occupied by the almost charismatic figure of Pietro Righini. At the same time organology researchers felt the need of better checking the variability of musical phenomena. So, apart from chemical methods, metallurgy, and dendrochrono-chronology, they appealed to musical acoustics. In 1985, during the international Meeting on Preservation, Restoration, and Re-Utilization of Old Musical Instruments, in Venice precise suggestions were made about the studies on stringed instruments (Pietro Righini, Giuseppe Righini, Sergio Cingolani). Vinicio Gai and Marco Tiella, two well-known organology scientists, were the actual promoters of this ‘New Renaissance’ of a systematic view about musical instruments. Certainly, these scholars conveyed their professional knowledge of international museologic requirements to the study and the preservation of musical instruments, being Vinicio Gai the director of the Musical Instruments Museum in Florence and Tiella the chairman of the Stringed Instruments Triennial Board in Cremona.

At present, many efforts have been done (and many will be done in future) as well as many years have passed from the beginning of so-called scientific research on the subject Cingolani [5]. Conceptualization is actually confronted with the most advanced technological contributions ever possible about scientific research on stringed instruments; and all this leaves the question open with regards to the fact that a musical instrument is necessary in producing music but not in determining its characteristics.

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Aspects of Bowed-String Dynamics

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Many relevant aspects of the bowed-string dynamics can be readily implemented using a modal method for numerical simulations. Some of these aspects are the subject of the present communication, namely: (1) the string inharmonic behaviour; (2) the finite width of the bow; (3) the string torsion modes. We start by reviewing our computational method, which consists in projecting the frictional forces on the transverse and torsion modes of the unconstrained string. The friction model developed is able to cope with both sliding and adherence states, using an explicit time-step integration method. We then discuss the above-mentioned dynamical aspects and present a few illustrative computations.

INTRODUCTION

We recently developed a modal-based method for the numerical simulation of bowed systems \cite{1-4}. Although still unable to achieve real-time performance, our approach enables very detailed modelling of the non-linear friction interaction forces, as well as an accurate representation of the string dynamics, in both time and space.

Furthermore, many relevant aspects of the bowed-string can be readily implemented when numerical simulations are based on a modal approach. We have recently explored several such aspects, which are the subject of the present communication, namely: (1) the string inharmonic behaviour; (2) the finite width of the bow; (3) the string torsion modes. We feel that some of these aspects have not been fully exposed in the literature — see, for instance, references \cite{5-8}.

We start by quickly reviewing our computational method, which is based on a modal approach, using an explicit time-step integration algorithm. In our implementation, we used a simple Verlet scheme.

We then briefly discuss the above-mentioned aspects and conclude with some relevant illustrative computations. The main purpose of this paper is to highlight the capabilities of the computational method. Thorough discussions of the dynamical results will be presented elsewhere.

COMPUTATIONAL METHOD

Any solution of the string PDE can be formulated in terms of the modal parameters $m_n$, $\omega_n$, $\zeta_n$ and modeshapes $\phi_n(x)$, $n = 1, 2, \ldots, N$:

$$[M]\ddot{Q}(t) + [C]\dot{Q}(t) + [K]Q(t) = \Xi(t) \quad (1)$$

The modal forces $\Xi_n(t)$ are obtained by projecting the external force field on the modal basis:

$$\Xi_n(t) = \int_0^L F(x, t) \phi_n(x) \, dx \quad (2)$$

The physical motions are computed from the modal amplitudes $q_n(t)$ by superposition:

$$y(x, t) = \sum_{n=1}^{N} \phi_n(x) q_n(t) \quad (3)$$

and similarly for the velocities and accelerations.

The previous system of equations can be integrated using an explicit time-step integration algorithm. In our implementation, we used a simple Verlet scheme. To solve equations (1-3), we include in $\Xi_n(t)$ all nonlinear (frictional) effects. The modes of the linear system are then coupled by the nonlinear terms.

Consider the friction force arising when the bow is applied at location $x_c$ of the string:

$$F_n(x_c, t) = -\mu_s(\dot{y}_c) F_N \text{sgn}(\dot{y}_c) \quad \text{if } |\dot{y}_c| > 0 \quad (4,5)$$

$$F_n(x_c, t) = \mu_s F_N \quad \text{if } |\dot{y}_c| = 0$$

where $\dot{y}_c$ is the relative transverse velocity between the bow and the string, $F_N(t)$ is the normal bow/string force, $\mu_s$ is a “static” friction coefficient (during adherence) and $\mu_s(\dot{y}_c)$ is a “dynamic” friction coefficient (during sliding). We use the following exponential model:

$$\mu_s(\dot{y}_c) = \mu_d + (\mu_s - \mu_d) e^{-C |\dot{y}_c|} \quad (6)$$

where, $0 \leq \mu_d \leq \mu_s$ and $C$ controls the decay rate of the friction coefficient with the sliding velocity.

When a near-zero velocity is detected at the contact point(s), the sliding force (4) is replaced by the following explicit model for adherence:
\[ F_a(x_c, t) = -K_a y_c(t) - C_a \dot{y}_c(t) \]  

The idea in (7) is to attach the string to the bow at point \( x_c \) using a suitable “adherence stiffness” and to damp-out any local residual motion with an “adherence damping” term — see [1] for details. The adherence force (7) is compared with the maximum allowable value (5). If this condition is not fulfilled, the system is sliding and formulation (4) is used.

**STRING INHARMONIC BEHAVIOUR**

Wave propagation in non-ideal (rigid) strings is dispersive. This effect is most easily simulated using a modal model, as the bending stiffness effect is automatically incorporated in the string modes, with modified frequencies \( \omega = n \omega_0 (1 + B n^2)^{1/2} \), where \( B \) is an inharmonicity coefficient [6]. Computations show that an increase in the string bending stiffness leads to a progressive “rounding” of the Helmholtz corner and, in general, to a deterioration of the response spectrum, as illustrated in Figure 1. Our results are compatible with previous investigations [6,8].

**FINITE WIDTH OF THE BOW**

Our computational model can be applied to finite-width bowing, simply by considering multiple adjacent contact points subjected to the friction interaction model. In general terms, our computations confirm the differential slipping mechanism, proposed by McIntyre et al. [5]. Small-scale slips during adherence are more frequent and pronounced for bow-hairs located near the bridge, a result that can be understood on simple geometrical terms. Simulations performed with many bow-hairs displayed complex spatial patterns of differential slipping, however without disrupting the mainly periodic string motions. Figure 2 shows a typical result from a 10 mm width bow, simulated by 10 equidistant bow-hairs. Two string velocity-plots are shown at the locations of the extreme bow-hairs.

**STRING TORSION MODES**

Inclusion of torsion and/or axial dynamic effects in our simulation method also presents no conceptual difficulties. One only has to include the new relevant modes in the computational scheme. Transverse and torsion modes are heavily coupled by the friction forces. Beyond the additional damping, inclusion of the string torsion modes can affect both the transient durations and the steady state regimes, depending on the ratio of propagation wave-speeds \( \alpha = c_{tor}/c_{tra} \). Indeed, opposing a conclusion from the restricted analysis [8], our systematic simulations suggest that torsion should not be neglected if \( \alpha < 4 \). Gut strings should then be particularly prone to torsion effects.

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Psychoacoustic Aspects of Violin Sound Quality and its Spectral Relations

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The term 'sound quality' expresses timbre, enumeration of sound properties, or sound evaluation. Sound quality assessment depends on the evaluator and evaluation purpose. Psychoacoustics studies selected aspects of sound quality in a chosen sound and listener context. An experiment establishing sound quality preference and its spontaneous word description on five violin tones H3, F#4, C5, G5 a D6 is described. Connections of sound quality preferences to sound context, frequencies of occurrence of descriptive words, and spectral features of the sound are discussed. Common properties of stationary spectra of a high quality violin tone are formulated: a sufficient level of the fundamental; deep and narrow notches and well pronounced and filled elevations in specified frequency regions; and a balanced consecutive decrease of levels of harmonics across elevation bands.

SOUND QUALITY AND PSYCHOACOUSTICS

The term 'sound quality' can represent a common property of sound (timbre), enumeration of sound properties (distinctive features) or aesthetic evaluation of sound (preference). The listener, musician, and instrument maker perceive quality of the sound of a musical instrument differently. The complete set of features of musical instrument sound quality consist of: dynamic properties; players instrument control; timbre aspects of individual tones and their balance in the whole dynamic range and diapason; possibilities to modifying the sound and achieving the required sound impression.

The goal of psychoacoustics is to ascertain the properties of the interaction of sound and human consciousness and express its causal relations. Psychoacoustic research may focus on defined sound quality aspects and a specific sound context. The goal of one experiment carried out in our laboratory was to study sound quality as a set of timbral properties in words and quality evaluation.

EXPERIMENT

The violin sound quality was studied on recordings of tones H3, F#4, C5, G5, and D6 of eleven instruments of various qualities recorded in an anechoic room and played détaché, naturale, non-vibrato, and mezzoforte. The duration of all tones and their transients and transient shapes were unified [1]. A pair test with headphones was administrated with ten listeners. Perceived sound quality preferences and spontaneous word descriptions of timbre differences for each pair of sounds were registered. Using this data, individual and group preferences and later individual and group ranks in perceived sound quality were calculated. Internal consistency of individual preference judgements and concordance of individual ranks in the group of judges were established in all five studied tones. Correlations between sound quality ranks and frequencies of occurrence of individual words were also calculated. Amplitude spectrum, SPL in individual harmonics, and spectral center of gravity were calculated from quasi-stationary part of signals [1]. These spectral properties together with word descriptions and determined quality preferences were used to interpret the results.

RESULTS AND DISCUSSION

Only words with an overall frequency of occurrence of at least ten were evaluated. This represents 65 words for the H3 tone, 64 for F#4, 58 for C5, 64 for G5 and 65 for D6 tone. Correlations of occurrence of selected words with sound quality evaluation rank are found in Table 1. These twenty words belong to the thirty most frequently used in all five tones. The words clear, voiced, damped, unvoiced have highly significant correlation only in the G5 tone; this implies that this tone sound quality preference was based on different sound properties than other tones.

It is possible to observe a division of tested tones in two groups – H3, F#4, C5 and G5, D6 – based on the frequency of occurrence of the words dark and clear (Table 2). The words voiced, damped
Interesting correlations between sound quality ranks and some spectral characteristics are found in Table 3, where the G5 note is again exclusive. Comparing spectral envelopes of different quality sounds with the envelope of the highest quality sound, and comparing the envelope of the best tone in all five tested pitches enabled formulation of a hypothesis on the spectral shape of a high-quality violin tone [1]: The harmonic spectrum of a high-quality violin tone has a sufficient level of the fundamental; its envelope is characterized with deep and narrow notches N0-N4 and wide, well-pronounced and filled elevation bands E1-E4 in frequency regions given in Figure 1; and it has balanced consecutive decrease of levels of harmonics across elevation bands.

A steeper decrease of the spectral envelope in the H3, F#4, and C5 tones versus G5 and D6 (Figure 1) agrees with frequencies of use of the words *dark* and *clear* in the description of sound properties (Table 2). With increasing pitch it becomes more frequent that no harmonic falls into the notch, and the spectrum envelope of a high-quality tone fills and smooths out. This may be the probable reason for the connection of quality evaluation in the G5 note with different words which describe other percepts induced through other spectral envelope properties.

Subjective evaluation of the quality of violin sounds depends on the number of spectral properties, which listeners describe in appropriate and different words. Spectral properties and their descriptive words can feature in various combinations and to different degrees consistently with listened sound context.

**Table 1.** Correlations between sound quality ranks and frequency occurrence of words used for timbre description. Significance: bold α≤0.01, normal α≤0.05, italics α≤0.1.

<table>
<thead>
<tr>
<th></th>
<th>H3</th>
<th>F#4</th>
<th>C5</th>
<th>G5</th>
<th>D6</th>
</tr>
</thead>
<tbody>
<tr>
<td>balanced</td>
<td>.67</td>
<td>.32</td>
<td>.81</td>
<td>.62</td>
<td>.82</td>
</tr>
<tr>
<td>clear</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>.82</td>
<td>–</td>
</tr>
<tr>
<td>dark</td>
<td>.86</td>
<td>.78</td>
<td>.57</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>delicate</td>
<td>.73</td>
<td>.57</td>
<td>.88</td>
<td>.85</td>
<td>–</td>
</tr>
<tr>
<td>full</td>
<td>.80</td>
<td>.76</td>
<td>.91</td>
<td>.86</td>
<td>–</td>
</tr>
<tr>
<td>pure</td>
<td>.67</td>
<td>.60</td>
<td>–</td>
<td>.63</td>
<td>.55</td>
</tr>
<tr>
<td>round</td>
<td>.83</td>
<td>.83</td>
<td>.70</td>
<td>–</td>
<td>.79</td>
</tr>
<tr>
<td>smooth</td>
<td>.78</td>
<td>.77</td>
<td>.88</td>
<td>–</td>
<td>.79</td>
</tr>
<tr>
<td>soft</td>
<td>.65</td>
<td>.75</td>
<td>.69</td>
<td>–</td>
<td>.78</td>
</tr>
<tr>
<td>voiced</td>
<td>–</td>
<td>–</td>
<td>.80</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>wide</td>
<td>.64</td>
<td>.70</td>
<td>.75</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>blearly</td>
<td>-.86</td>
<td>-.57</td>
<td>-.75</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>damped</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>-.76</td>
<td>–</td>
</tr>
<tr>
<td>metallic</td>
<td>-.74</td>
<td>-.73</td>
<td>-.77</td>
<td>–</td>
<td>-.72</td>
</tr>
<tr>
<td>narrow</td>
<td>-.79</td>
<td>-.70</td>
<td>-.87</td>
<td>-.90</td>
<td>–</td>
</tr>
<tr>
<td>penetrating</td>
<td>-.84</td>
<td>-.73</td>
<td>-.67</td>
<td>–</td>
<td>-.88</td>
</tr>
<tr>
<td>rustle</td>
<td>-.62</td>
<td>-.61</td>
<td>-.66</td>
<td>–</td>
<td>-.62</td>
</tr>
<tr>
<td>sharp</td>
<td>-.72</td>
<td>–</td>
<td>-.63</td>
<td>–</td>
<td>-.75</td>
</tr>
<tr>
<td>tinny</td>
<td>-.77</td>
<td>-.75</td>
<td>-.83</td>
<td>–</td>
<td>-.86</td>
</tr>
<tr>
<td>unvoiced</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>-.78</td>
<td>–</td>
</tr>
</tbody>
</table>

**Table 2.** Contrasts in ranks of overall frequency occurrence of selected words in individual tones, high ranks are bold.

<table>
<thead>
<tr>
<th></th>
<th>H3</th>
<th>F#4</th>
<th>C5</th>
<th>G5</th>
<th>D6</th>
</tr>
</thead>
<tbody>
<tr>
<td>sharp</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>dark</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>clear</td>
<td>15</td>
<td>10</td>
<td>8</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>narrow</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>voiced</td>
<td>16</td>
<td>11</td>
<td>20</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>damped</td>
<td>26</td>
<td>23</td>
<td>13</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>rustic</td>
<td>14</td>
<td>12</td>
<td>30</td>
<td>18</td>
<td>6</td>
</tr>
</tbody>
</table>

**Table 3.** Correlations between sound quality ranks and spectral characteristics. Significance see Table 1.

<table>
<thead>
<tr>
<th></th>
<th>H3</th>
<th>F#4</th>
<th>C5</th>
<th>G5</th>
<th>D6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of the 1st harmonic</td>
<td>-.55</td>
<td>-.57</td>
<td>-.82</td>
<td>.79</td>
<td>.52</td>
</tr>
<tr>
<td>Spectral center of gravity</td>
<td>-.80</td>
<td>-.77</td>
<td>-.62</td>
<td>-</td>
<td>-.63</td>
</tr>
</tbody>
</table>

**FIGURE 1.** Harmonic spectra of the highest sound quality violin tones and positions of notches (Ni) and elevations (Ei).

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On the Precision of the Pitch Sensation in Sound of Bowed Instruments

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Frequency discrimination thresholds, DLs, were measured with the use of an adaptive, two-interval, forced-choice procedure, for tones played on bowed instruments and for pure tones. Results show that DLs obtained for musical tones are relatively small, and range from 4 to 6 cents in most pitch registers. Frequency DLs determined for pure tones are in close agreement with those obtained for musical tones in all but the low pitch register. In the lowest pitch register, the DLs of pure tones are by about ten times higher than DLs determined for musical tones. The DL values obtained in the present study are taken as a direct reciprocal measure of the pitch strength (the precision of pitch sensation) of tones under investigation.

INTRODUCTION

Among the bowed stringed instruments, violin is known for its high precision of pitch control. In contrast, the double bass, which produces sounds of the lowest pitch register used in music, is often considered an instrument with a hard-to-define pitch.

The precision of pitch sensation is called pitch strength. Pitch strength may be derived from the measurement of frequency discrimination. The purpose of the present study was to assess the pitch strength of bowed instrument tones and of pure tones with the use of an adaptive, two-interval, two-alternative, forced choice procedure (2I, 2AFC).

PITCH STRENGTH OF BOWED INSTRUMENT TONES

Frequency discrimination of bowed instrument tones was measured with the use of an adaptive, two-interval, two-alternative forced choice adaptive procedure with feedback [1]. The stimuli were two tones (D1 and B1) played on a double bass, two tones (E2 and A2) played on a cello, and three violin tones (G#5, G6, and F#7). All tones were presented diotically at a loudness level of 75 phons. Tone duration was 2 s.

The tones were recorded digitally at a sampling rate of 44.1 kHz and stored on a computer hard disc. A PC-compatible computer with a TDT AP2 signal processor controlled stimulus presentation and the adaptive procedure. The sound file was played back by a DD1 D/A converter, led through an FT5 antialiasing filter, two PA4 attenuators, and an HB6 amplifier to a Beyerdynamic DT 911 headphone set. On each trial, the subject heard two tones presented in random order: a tone at its original frequency $f$, and a tone at a frequency of $f + \Delta f$, and was requested to indicate which of the tones had a higher pitch. The subject received visual feedback on the response box.

The tone frequency was varied by changing the sampling rate during playback, according to a two-down/one-up decision rule that estimated the 70.7% correct point on the psychometric function. Each run started 10 Hz above the original tone frequency and terminated after 50 trials. The size of $\Delta f$ was changed by a factor of $r$. The value of $r$, initially set at 1.58 ($\log(1.58) = 0.2$), was reduced to 1.26 ($\log(1.26) = 0.1$) after two reversals of signal frequency. The threshold was estimated as the geometric mean of $\Delta f$ at the reversals, following the fourth reversal. Four students with normal hearing served as subjects. Each subject completed six series of runs.

Figure 1 shows the group means and standard deviation of DLs, calculated in cents. Results indicate that the DL is almost invariant in a pitch range from B1 to G6, and ranges from 4 to 6 ct. The DLs obtained for the lowest double-bass tone, D1, corresponding to a fundamental frequency of 36.7 Hz, and the highest violin tone (F#7, 2794 Hz) are appreciably larger, and so is the standard deviation of data.

![Figure 1. Frequency DLs for bowed instrument tones. Group means and standard deviation across four listeners.](image-url)
Frequency Discrimination thresholds for pure Tones

In order to compare the frequency DLs determined for musical tones with data obtained for pure tones, frequency discrimination in pure tones was measured using the same adaptive 2I, 2AFC procedure, at 14 frequencies spanning a range from 25 to 8000 Hz. Three students who also participated in the previous experiment served as subjects. Each subject completed five series of adaptive runs. The setup was the same as in the previous experiment except that the tones were not stored on hard disk, but generated by a DD1 D/A converter, and presented monaurally. The tone sensation level was 20 dB at 25 and 31.5 Hz, 30 dB at 40, 50, and 63 Hz, and 40 dB at 80 Hz and higher frequencies. Sensation levels were set for each listener individually. Individual detection thresholds, corresponding to a 70.7% correct point on the psychometric function were measured in a preliminary experiment, with the use of an adaptive, 2I, 2AFC procedure.

Figure 2 presents the group means and standard deviation of DLs obtained for pure tones. The data are shown in cents.

![Figure 2](image)

**FIGURE 2.** Frequency DLs for pure tones. Group means and standard deviation across three listeners.

To enable a comparison of DLs obtained for musical tones and pure tones, the data plotted in Figs. 1 and 2 have been combined in Fig. 3. Figure 3 also shows the values of frequency DL for pure tones, obtained by Wier et al. [2] with the use of a 2I, 2AFC procedure.

**FIGURE 3.** A comparison of frequency DLs obtained for bowed instrument tones and for pure tones.

**Discussion and conclusions**

The measurements of frequency DLs of bowed instrument tones have shown that the pitch strength of bowed instruments is uniform in the greater part of the musical scale. Only the lowest tone of the double bass and the highest tone of the violin show an about two-fold increase of their frequency discrimination threshold measured in cents.

In light of the above finding, an opinion shared by many musicians, that the pitch of double bass tones is less clearly defined than that of the other bowed instruments, requires some correction.

In the lowest musical pitch register, frequency DLs of double-bass and cello tones, measured in cents, are about 10 times smaller than DLs for pure tones (Fig. 3). The frequency DL of a pure tone is on the order of a semitone at frequencies below 50 Hz. The high sensitivity to changes of low musical tones in frequency is an effect of the presence of overtones in the sound spectrum, as reported in other studies, e.g. [3].

The physiological mechanism of pitch discrimination is related with various phenomena described by the place theory and the temporal or time theory (see [4] for a discussion of experimental data). Due to the mechanical properties of the basilar membrane, the mechanism of pitch discrimination, based on the place theory, becomes ineffective at very low frequencies. At very low frequencies, pitch is identified and differentiated on the basis of the time pattern of neural impulses evoked by the sound, and the presence of overtones facilitates pitch discrimination.

**ACKNOWLEDGMENTS**

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**REFERENCES**

THE BH-PEAK OF THE VIOLIN AND ITS RELATION TO CONSTRUCTION AND FUNCTION

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The violin bridge has its first in-plane resonance at approximately 3 kHz. Experiments, measuring bridge mobility, prove that the BH-peak between 2 and 3 kHz of an assembled violin is not confined to this resonance only. By exchanging a normal bridge to a bridge blank with its first in-plane resonance at approx. 8 kHz the BH-peak remains mainly unchanged. Also, the main properties of the BH-peak of a Stradivarius violin and a newly assembled violin are different, but independent of bridges. Comparisons between bridge mobility and radiated sound display similarities but the similarities are not easily reproduced. Analysis of played scales proved that the tonal spectra are limited up to somewhat above the BH-peak frequency. Played tonal spectra are limited to approx. 4 kHz although the radiation of a violin generally extends to much higher frequencies. However, this frequency limitation is at least partly caused by string inharmonicity, which increases considerably above the BH-peak frequency.

INTRODUCTION

Previously a new professionally made violin (S Niewczyk) of good quality was measured with its original bridge and an especially made bridge blank [1]. The bridge blank was made of bridge maple and shaped as a violin bridge but without the traditional cut-outs as “heart”, “ear”, “nose” etc. Measured properties as bridge mobility of the new Niewczyk violin were found to be closely the same in spite of 3.0 kHz resonant frequency of the bridge and 7.6 kHz of the blank.

The Sound radiation of 11 Italian Master Violins measured by Dünnwald and the Bridge mobility measured by Jansson show rather similar frequency responses in the 1.5 to 3.5 kHz range [2,3]. Thus it may be concluded that the 2.3 kHz BH-peak is not confined to the first in-plane resonance alone and that the BH-peak shows up both in bridge mobility and sound radiation. But what is its relation to the construction and to the function of a violin?

NEW AND OLD VIOLIN

The properties, measured as bridge mobility, of a Stradivarius violin typically show a broad rounded BH-peak in the 2-3 kHz range, see Fig. 1. The same bridge on the newly made Niewczyk violin shows a prominent, rather marked peak in the same frequency range. Thus experiments indicate again that the BH-peak again is mainly set by the violin and not by the bridge. Furthermore laboratory experiments with experimental violins indicates that the violin top plate is a construction parameter determining the main properties of the BH-peak rather than the violin bridge.

TWO VIOLINS WITH DIFFERENT BH-PEAKS

The bridge mobility was measured of two good reference violins, one with a more brilliant tone (LB) than the other (GL), see Fig. 2. The LB-violin has a more clear BH-peak maximum just below 2 kHz. The GL violin has no clear such peak maximum, but rather a smooth peak maximum. The level of the mobility response around 2 kHz is also somewhat higher for the LB violin.

The sound radiation of the two violins was measured in different directions in the anechoic chamber of the Norwegian Technical University, NTNU, using a newly developed technique, see fig 3 [4]. The level of radiated sound varied greatly with direction but the averages as shown in fig 3 becomes rather stable with an average over a moderate number of directions. Again it can be seen that the LB violin has a more...
prominent BH-peak at 2 kHz than the GL violin. The frequency region marked with horizontal lines at the same level shows the more collected and higher level response for the BL violin.

**BH-PEAK AND PLAYED TONES**

Long-time-average spectra of full-tone scales played on the four strings of a violin indicate a maximum at approx. 3 kHz followed by steep slope cutting off higher frequency components (the LTAS-diagrams are plotted with properties of the hearing included), see Fig. 4 [5]. The spectra indicate that the cut-off is a general and a wanted property. Recent experiments indicate that string inharmonicity may be the dominant factor here rather than boundary conditions set by the "non-rigid" end support, the violin bridge.

Thus our study indicates that the bridge mobility predicts the BH-peak in the radiated sound signal, but averaging over many directions is needed to remove directional "masking", and that string properties in playing also can enhance the BH-peak.

**ACKNOWLEDGEMENTS**

The sound radiation measurements were made by LH Morset at NTNU, Trondheim in cooperation with the first author.

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Measurements of radiation efficiency and internal mechanical loss applied to violins

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Internal mechanical losses were determined by measuring the normalized radiated power and the real part of the mobility at the bridge. Radiated power was determined by measuring the far-field sound pressure in an anechoic room at a spherical surface with a radius of 1.05 m and an angular resolution of 22.5 degrees. The total power transferred to the violin at the bridge is determined as the real part of the input mobility, \( \text{Re}[Y] \). The two violins tested had radiation efficiencies that varied with frequency and had an average of 1.54 % and 1.24 % in the frequency range 200-3000 Hz.

INTRODUCTION

The main goal of this study was to test a method for accurate measurement of internal mechanical loss and radiation efficiency of violins. The method described can be applied to different types of acoustical sources and e.g. plates as well. In order to obtain the mechanical loss, two types of measurements were performed: 1) Measurement of the radiated power normalized with respect to the force, \( \text{Power}_{\text{rad, norm}} \) 2) Measurement of the input mobility. The real part of the input mobility, \( \text{Re}[Y] \), gives the total normalized power transferred to the violin, which is the sum of the radiated power and the mechanical loss. This gives the radiation efficiency, \( \eta \):

\[
\eta = \frac{\text{Power}_{\text{rad, norm}}}{\text{Re}[Y]}
\]

In this study, two violins were measured, a new unconventional model built by Hagetrø Fioliner® and an old top-quality Stradivari copy built by J. P. Thibout in Paris 1843.

RADIATED POWER MEASUREMENT

The normalized radiated power was found measuring the far-field sound pressure in an anechoic room using two microphones to scan a sphere with a radius of 1.05 m and an angular resolution of 22.5 degrees. The relatively small radius may introduce an error in the far field approximation (at low frequencies). However, previous measurements indicate that the radius and the angular resolution are sufficient in the frequency range 200 Hz to 10 kHz.

 Erotision AND MOUNTING

The mounting method will affect the acoustic properties of the violin. Here, the violin was held with pieces of rubber at the bottom part of the body and the upper part at the neck. A custom-made force transducer used a 60 mg magnet, attached with wax at the G-string side of the bridge, and a small coil positioned near the magnet. Pseudo-random noise (MLS) was used as excitation signal, using the software WinMLS® and the force was directed parallel to the top-plate. The force transducer was calibrated and can be used up to 8 kHz. Alternative methods of excitation would be using a hammer, but that would give a decreased signal-to-noise ratio for the acoustic measurements, and an electrodynamic shaker would add more weight to the violin bridge than the small magnet that was used. To make the conditions equal, the violins were mounted and excited exactly the same way in the measurements described in the two chapters below.

INPUT POWER MEASUREMENT

The power transferred to the violin at the bridge was found as the real part of the input mobility, \( \text{Re}[Y] \), by measuring the velocity in the same plane as the excitation at the bridge using a laser vibrometer. The laser beam can be pointed through the coil at the magnet and thus the force and the velocity can be measured in exactly the same point, which in principle
should be the optimum measurement point. Here, however the velocity was measured at the opposite side of the bridge since measuring through the coil gave less stable results (this will be investigated further). Measuring the mobility of the violin bridge this way is common [2]. This method does not depend on an anechoic room, and it can be fast, simple and inexpensive. A laser vibrometer is preferred to an accelerometer for measuring the velocity because it adds no weight to the bridge.

RESULTS

Fig. 1 shows the results for the Thibout violin. It has a wolf tone at C (525.6 Hz). The peak of Re[Y] was found exactly at this frequency, which shows that it is possible to accurately measure wolf tones using this setup. At this frequency, the mobility of the bridge is large, the bridge simply moves so much that it is impossible for the string to maintain a standing wave.

FIGURE 1. The curves show, from the top, the total normalized power (Re[Y]), the normalized radiated power, and the radiation efficiency (dotted line) for the Thibout violin.

Fig. 2 shows the results for the Hagetrø violin. The average radiation efficiency in the frequency range 200-3000 Hz was computed to 1.24 % for the Thibout violin and 1.54 % for the Hagetro violin. The maximum value was ~5 % (-26 dB) and was found in the frequency range 1.2-1.3 Hz for both violins. From the figures we see that the radiation efficiency depends largely on frequency, but does not show an increasing or decreasing trend. The repeatability of the measurements was good.

FIGURE 2. The curves show, from the top, the total normalized power (Re[Y]), the normalized radiated power, and the radiation efficiency (dotted line) for the Hagetrø violin.

CONCLUSION

A method for the accurate measurement of the radiation and the losses in a violin has been presented. The method can be fast (~15 minutes per violin if a 8-channel system is used). The results will tell which modes are efficient radiators. Further work will include a study of the relationship with the modal shape and the radiation efficiency. For the two violins measured the radiation efficiency in the frequency range 200-3000 Hz was measured to be 1.54 and 1.24 %, having peak values at ~5 %. Since the radiation efficiency is small and depends largely on frequency, measurement of the mobility at the bridge will not indicate all factors affecting the quality of a violin.

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REFERENCES


Modal and Acoustic Analysis On The Violin Octet

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Modal analysis was performed on a complete Hutchins-Schelleng violin octet, along with A0 and A1 cavity mode analysis and room-averaged acoustic analysis, to help characterize the dynamic characteristics of the octet. Signature corpus and cavity modes were tracked across the octet, along with acoustic radiativity characteristics of each mode. The main air and main wood resonance results are compared with Schelleng’s scaling predictions.

INTRODUCTION

John Schelleng, in collaboration with Carleen Hutchins, worked out physical scaling equations to scale the violin to other pitch ranges [1]. Schelleng made the substantial, limiting assumptions of flat plates and similar shapes for all the instruments, and restricted the scaling to the “main air” (A0) and “main wood” (B1) resonances only. A later, complicating development was the retroactive inclusion of the A1 cavity mode in the main wood resonance by Hutchins[2]. A1 is the lowest cavity length mode that scales directly with instrument length. Schelleng’s scaling laws all had length dependences to the 2nd or 4th power, however, presenting an inherent conflict with A1 scaling.

EXPERIMENT AND ANALYSIS

As part of the VIOCADEAS Project experimental modal analysis, cavity mode analysis, and room-averaged acoustic analysis on a complete violin octet was combined to judge the overall success of the scaling. The modal analysis of a violin suspended in approximate “free-free” conditions employed force hammer impact excitation at the bridge on the bass bar side and a scanning laser vibrometer to measure the velocity response. These were combined to create mobilities \( Y(\omega) \) over the entire violin including all major substructures. Strings were undamped (but unmeasured).

Cavity mode analysis employed two interior microphones placed in the upper and lower bouts and internal or external acoustic excitation. Room-averaged acoustic radiation was recorded for later analysis using hammer impact excitation with a sound quality head connected to a DAT recorder.

Modal analysis measurements were analyzed to extract mode frequencies, dampings and shapes. Certain signature shapes were classified and tabulated for each instrument and correlated across the octet. The A0, A1, A2 and A4 cavity modes induced “mirror modes” in the corpus that allowed ready identification (A0 and A1 were also observed in cavity acoustic spectra). In Figure 1 normalized, room-averaged pressure results were superimposed over normalized summed-over-top-and-back-plate mobilities for comparison of mechanical vs. acoustic strength.

![Figure 1](image-url)

Figure 1 – Superimposed normalized averaged corpus mobility (thin line, shaded) and room averaged acoustic pressure (thick line) for mezzo, tenor and large bass. Desired scaling positions for A0 and B1 noted with arrows. Note B1+ doublets for tenor.
DISCUSSION

The summary mode frequency results for the entire octet are given in Table 1. These have been normalized to the frequency of the lowest string and to the desired scaling placement so that the success of the intended scaling can be judged. The original scaling attempted to place the A0 resonance seven semitones, and the B1 resonance 14 semitones above the lowest string. Comparisons with Schelleng’s “main wood” resonance placement was complicated by the fact that it now includes three disparate components A1, B1̄ and B1+̄. A further complication arose when the latter two showed signs of coupling to substructures like the neck-fingerboard and the tailpiece. For comparison purposes with the original “main wood” scaling all the B1 corpus mode frequencies have been averaged. Perfect scaling would then be denoted by values of 1 in Table 1.

Table 1 – Ratios of A0 (“main air”) and “main wood” to intended scaling values.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>A0</th>
<th>A1</th>
<th>B1−</th>
<th>B1+</th>
<th>B1av</th>
</tr>
</thead>
<tbody>
<tr>
<td>treble</td>
<td>0.81</td>
<td>0.80</td>
<td>0.80</td>
<td>0.98</td>
<td>0.89</td>
</tr>
<tr>
<td>soprano</td>
<td>0.92</td>
<td>0.95</td>
<td>0.96</td>
<td>1.09</td>
<td>1.02</td>
</tr>
<tr>
<td>mezzo</td>
<td>0.91</td>
<td>0.96</td>
<td>0.94</td>
<td>1.09</td>
<td>1.02</td>
</tr>
<tr>
<td>alto</td>
<td>0.95</td>
<td>0.98</td>
<td>0.93</td>
<td>1.06</td>
<td>0.99</td>
</tr>
<tr>
<td>tenor</td>
<td>0.82</td>
<td>0.98</td>
<td>0.98</td>
<td>1.12</td>
<td>1.07</td>
</tr>
<tr>
<td>baritone</td>
<td>0.93</td>
<td>1.05</td>
<td>1.12</td>
<td>1.24</td>
<td>1.18</td>
</tr>
<tr>
<td>small bass</td>
<td>0.85</td>
<td>1.04</td>
<td>0.95</td>
<td>1.05</td>
<td>1.01</td>
</tr>
<tr>
<td>large bass</td>
<td>0.78</td>
<td>1.03</td>
<td>0.95</td>
<td>1.13</td>
<td>1.04</td>
</tr>
</tbody>
</table>

† doublet average value

Main Air – A0

All the instruments showed A0 falling below the intended placement. The poorest agreement was for the treble and large bass, the size extremes. Surprisingly the 4 largest instruments had already had their ribs cut back from the original heights, but still fell short of desired placement [2]. At least part of this failure was due to Schelleng’s (and Hutchins’) use of an insufficient theoretical model for A0, which neglected coupling with A1 and corpus compliance.

Main Wood – B1 (Corpus)

The B1 mode frequencies generally bracket the desired placement for the main wood. Since Schelleng’s scaling employed flat plate theory, this is a positive result that indicates that flat plate scaling provides a reasonable -- and analytical -- approximation for the violin octet scaling. The baritone was the only instrument that clearly failed to have the B1 modes bracket the desired placement (the treble had the B1+ mode coincide with the intended placement). Overall the “main wood” resonance placement was generally successful.

Main Wood – A1

For the two smallest instruments A1 fell right on top of the B1̄ mode. For all the larger instruments except the baritone A1 fell between B1̄ and B1+̄. This result is surprising due to the fact that A1 scales with the length, but all the larger instruments were dropped in size relative to “perfect” scaling [1]. The agreement is consistent with corpus compliance effects [4].

SUMMARY

The violin octet scaling of Schelleng was unsuccessful for the “main air” resonance because of a faulty theoretical model for A0 that did not include coupling to A1 or corpus compliance. The “main wood” scaling was generally successful.

ACKNOWLEDGEMENTS

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Average of the 18th Century Italian Violin Transfer Function

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For a long time many scientists, musicians, and violinmakers tried to reveal the secret of the famous old Italian violins. Acoustical properties of a musical instrument can be described by its transfer function and many results show that the transfer functions of each old instrument show slightly different but similar aspects. Sometimes it is significant to average transfer functions of violins for generalize the characteristic of violin. But arithmetic averaging has the same effect as low pass filtering and this can cause some loss of detailed peak data included in each transfer function, which determines the sound color of the instrument. To improve this, we propose PCA (Principal Component Analysis) based averaging technique with detailed peak information. For averaging, this method utilizes weight vector of each transfer function. By applying PCA to the transfer functions of the violins, some PCs and corresponding weight vectors are calculated. Then the averaged violin transfer function is reconstructed using the principal components and the averaged weight vector. In the present paper, the theoretical backgrounds and features of the proposed method are presented. Also, some results from experiments are presented. The original transfer function data of old violins are from Dünnwald's previous works.

INTRODUCTION

Sound color of a musical instrument can be described by its transfer function. It is a well known fact that transfer functions of famous old Italian violins show similar but slightly different aspects. To generalize the characteristic of them, averaging of their transfer functions will be useful. But arithmetic averaging causes low pass filtering effect. This means that detailed peak information in each transfer function can be lost. To avoid the loss of detailed peak information, we propose PCA [2] (Principal Component Analysis) based averaging technique. For averaging, this method utilizes weight vector of each transfer function. By applying PCA to the transfer functions of the violins, some PCs and corresponding weight vectors are obtained. Then averaging is carried on the weight vector. Finally, the averaged violin transfer function is reconstructed using the PCs and the averaged weight vector. Because PC contains featured patterns of the curve and weight vector represents only the portion of each PCs constituting the original curve, averaging the weight vector does not cause loss of the featured patterns. As a result, we can get the averaged transfer function without losing original transfer function’s detailed peak information that are lost in arithmetic averaging on the effect of low pass filtering. The transfer functions of old Italian violins for the experiment are from Heinrich Dünnwald’s previous works. [1]

PREVIOUS WORKS

The sound generation mechanism of a violin can be described as follows; 1) bow excites the string, 2) the motion of excited string is transferred to body through bridge 3) radiation of sound. For acquisition of violin transfer function without the effect of the bowing and the characteristics of string, excitation is exerted on the violin directly at the bridge with some adequate functions. Transfer functions can be measured using impulse or sine sweep as the excitation functions. In case of impulse excitation, one can easily get the information including time variance, but enough SNR is not achievable. In case of violins, as the excitation is done by steady bowing, the time variance is relatively small. So, the transfer functions employed in this paper were all obtained through sine sweep method. [1]

FIGURE 1. Excitation Mechanism
AVERAGING ALGORITHM

The procedure of PCA based averaging of transfer function is shown in figure 2.

![Diagram of Averaging Algorithm]

**FIGURE 2.** Reconstruction of Transfer function using PCA

First we evaluate PCs that correspond to the patterns of transfer function and also evaluate corresponding weight vectors. Then preserving the PCs unaffected, we calculate the average of weight vectors. Finally we reconstruct averaged transfer function with pre-evaluated PCs and averaged weight vectors.

EXPERIMENT AND RESULT

**FIGURE 3.** Original transfer function to be averaged

The top picture of figure 4 is PCA based averaging of transfer functions and the bottom picture is arithmetically averaged transfer function. In this experiment, we used 8 Old Italian violins’ transfer functions. As we can see from figure 4, if we use arithmetical averaging, the detailed peak information in the frequency range above 1kHz is lost by the effect of low pass filtering. But if we use PCA based averaging, the properties including detailed peak information of original transfer functions are preserved well.

**FIGURE 4.** Comparison of PCA based averaging of transfer function and arithmetically averaged transfer function

CONCLUSION

It has been shown that if we use PCA to average transfer functions, the PCs that correspond to the patterns of transfer function do not affected by the process of averaging. Because the proposed algorithm does not average the PCs but averages just weight vector for averaged transfer function. That means we can preserve the patterns of original transfer function in averaging process. So we could get the averaged transfer function without loss of detailed peak information of original curve’s that are lost in arithmetic averaging on the effect of low pass filtering.

REFERENCES